

Role of Final-State Interaction Modeling in Neutrino-Energy Reconstruction and Oscillation Measurements

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We present a quantitative demonstration that, without additional theoretical and experimental efforts, realistic variations in final-state interaction (FSI) modeling may alter reconstructed neutrino-energy spectra at next-generation long-baseline experiments by amounts comparable to, or larger than, variations induced by oscillation-parameter shifts at their projected precision. Using the DUNE flux and baseline as a case study, we show that these FSI-driven distortions can mimic the effects of changes in the oscillation parameters Δm_{32}^2 or δ_{CP} , producing a potential degeneracy. Our analysis thereby underscores the urgent need for an improved characterization of FSI to enable robust constraints from near detectors through the development of theory-driven uncertainty parameterizations benchmarked with dedicated new measurements.

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Introduction—Long-baseline (LBL) neutrino oscillation experiments are essential for advancing our understanding of neutrino properties through measurements of $\bar{\nu}_\mu$ disappearance and $\bar{\nu}_e$ neutrino appearance in an $\bar{\nu}_\mu$ neutrino beam. Future experiments, the Deep Underground Neutrino Experiment (DUNE) [1] and Hyper-Kamiokande (HK) [2,3], will dramatically improve measurements on neutrino oscillation parameters, determine whether there is charge-parity (CP) violation in the lepton sector, resolve the neutrino mass ordering, and search for signatures of new physics [3,4].

A vital component of these measurements is the precise reconstruction of the incoming neutrino energy from the visible products of neutrino interactions with the nuclear targets within detectors [5]. This is particularly important for experiments like DUNE that are designed with a broadband neutrino beam and will infer oscillation probabilities over a wide energy range. The core technology of the DUNE detectors is the liquid argon time projection chamber (LArTPC), which can provide a detailed reconstruction of neutrino interaction products

following neutrino interactions with argon nuclei [1]. The reconstruction of the incident neutrino energy relies on summing the energy of the visible interaction products. Since different particles leave different fractions of their energy as visible signatures in a LArTPC, the accuracy of neutrino-energy reconstruction depends on the modeling of the constituents of the hadronic final state. This is sensitive to final-state interactions (FSI), where hadrons produced in the initial neutrino interaction undergo further scattering inside the nucleus before exiting, altering observable particle multiplicities and kinematics [5,6].

In this work, we use simulations of neutrino interactions with different FSI models with the DUNE neutrino flux [1,7] and baseline (1300 km) as a case study to assess how different FSI models affect reconstructed neutrino energies and the resulting energy spectra. We then provide a novel comparison of the size of these distortions to variations of oscillation parameters at the level of precision that future LBL experiments aim to measure [3,8].

Method and models—Charged-current neutrino interactions with argon are generated using the GENIE v3.04.00 neutrino event generator [9,10] using a fixed neutrino-nucleus interaction model (described below) apart from alterations to the simulation of FSI. Electron and muon neutrino and antineutrino interactions are generated using fluxes expected at the DUNE near detector [1,7] and then weighted to apply oscillations using the PROB3++ software package [11,12]. The baseline set of neutrino oscillation parameters considered are $\sin^2 \theta_{12} = 0.307$, $\sin^2 \theta_{13} = 0.0219$, $\sin^2 \theta_{23} = 0.558$, $\Delta m_{21}^2 = 7.53 \times 10^{-5} \text{ eV}^2$, $\Delta m_{32}^2 = 2.455 \times 10^{-3} \text{ eV}^2$, taken from Ref. [13], $\delta_{CP} = 0$ by default, and a normal neutrino mass

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ordering. Matter effects are treated using the default implementation within `PROB3++` [11,12].

The baseline interaction model uses the `G18_10a_00_000` GENIE configuration [14], employing a local Fermi-gas nuclear ground state, the Valencia group's model for charged-current quasi-elastic and $2p2h$ interactions [15–17], the Berger-Seghal pion production models [18,19], and GRV98 PDFs with Bodek-Yang corrections [20,21] for deep inelastic scattering. Hadronization is modeled either with `PYTHIA` [22,23] (at invariant masses, W , above $3.0 \text{ GeV}/c^2$) or the custom `AGKY` model [24] ($W < 2.3 \text{ GeV}/c^2$), and an interpolation between them [25].

FSI are simulated using one of the four different models available within GENIE: the default `hA2018` model, the `hN2018` model [14], the Liège intranuclear cascade model (`INCL`) [26], or the `GEANT4 Bertini Cascade` model (`G4BC`) [27]. Very broadly, `hA2018` and `hN2018` are widely used models that are tuned extensively to hadron scattering data, while `INCL` and `G4BC` are more sophisticated hadron transport models. Further details and comparisons of these FSI models are available in Supplemental Material [28] and in Refs. [6,56]. The span of these models provides a realistic *minimal* uncertainty envelope.

In this work, we define a proxy for reconstructed neutrino energy (E_ν^{rec}) as,

$$E_\nu^{\text{rec}} = E_\ell + \sum_{i=p} T_i + \sum_{i=\pi, K, \gamma} E_i. \quad (1)$$

This is the sum of the lepton energy (E_ℓ), the kinetic energies (T) of all final-state protons, and the total energy (E) of all pions, kaons (charged or neutral), and photons. No selection effects or energy thresholds are considered. We define the relative neutrino-energy bias as $(E_\nu^{\text{rec}} - E_\nu^{\text{true}})/E_\nu^{\text{true}}$.

Equation (1) assumes a neutrino detector, which acts as a perfect calorimeter for charged-particles and photons whilst also successfully identifying the multiplicity of charged pions. (Charged pion mass energy is lost largely to neutrinos from the pion decay, and thus it must be added to the calorimetric sum.) In this definition, the size of the bias is primarily driven by the amount of the interaction energy carried away by neutrons. (Other small contributions to bias may stem from nuclear binding energy.) This bias metric is broadly illustrative of what might be expected from DUNE's LArTPCs, which can use a combination of tracking and calorimetry to achieve this high precision for neutrino-energy reconstruction. The relationship between this proxy and the true neutrino energy depends on the modeling of effects that modify the visible energy in the detector, like FSI. Reference [57] provides a discussion of this reconstructed neutrino-energy metric and how it compares with others. The impact of detector smearing and reconstruction thresholds are studied in Supplemental

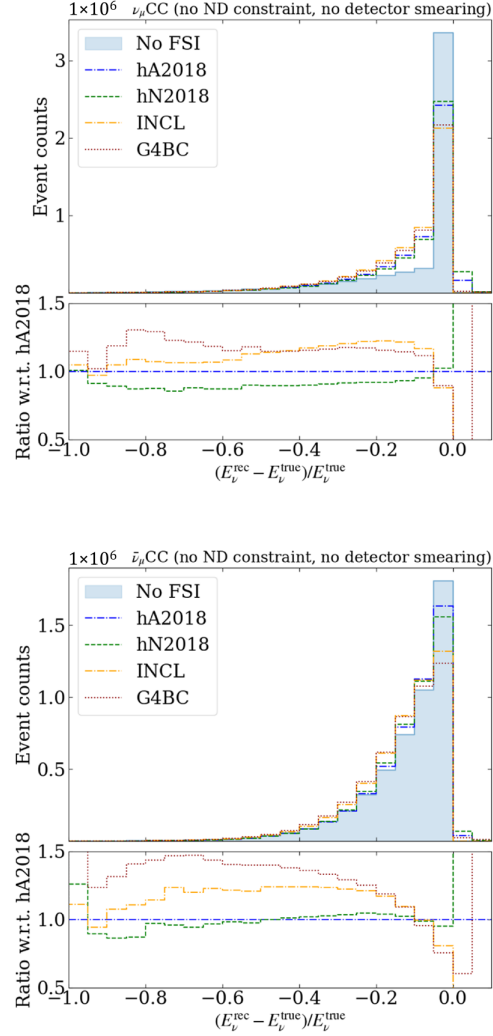


FIG. 1. Simulated distribution of relative neutrino-energy bias for 5×10^6 muon neutrino (top) and antineutrino (bottom) charged-current interactions, using the DUNE neutrino and antineutrino beam-mode fluxes respectively before oscillations occur, for a variety of different FSI models. The blue shaded histogram assumes no FSI, while the other histograms correspond to the four FSI models considered in this work. The bottom panel shows the ratios of different FSI model predictions with respect to the `hA2018` model.

Material [28] and found not to change the conclusions of this work.

Figure 1 shows the simulated distribution of the relative neutrino-energy bias for $\bar{\nu}_\mu$ charged-current interactions for each of the different FSI models, including one simulation without FSI. It is apparent that FSI has a significant impact on neutrino-energy reconstruction and that different FSI models lead to significantly different energy bias profiles. Moreover, we note that FSI, and the sources of invisible energy it introduces, has a different impact on the energy reconstruction of neutrinos with respect to antineutrinos. Whilst neutrino interactions occur primarily with neutrons

in the nucleus, and as a result often produce protons or other charged particles in the absence of FSI, antineutrinos reverse this behavior and produce more neutrons in the final state. This can be observed in the much broader distribution of the relative bias in the antineutrino case.

Variations to the reconstructed neutrino-energy spectra for $\bar{\nu}_\mu$ disappearance and $\bar{\nu}_e$ appearance channels from alterations of FSI modeling are compared to variations of neutrino oscillation parameters. The latter are chosen to be comparable to next-generation experiments' long-term projected precision [3,8]. For reference, these are also compared to expected statistical uncertainties on the measured reconstructed neutrino-energy spectra from a projected exposure of ten years of the DUNE experiment (corresponding to 624 kt-MW-years, equally split between beam operation in neutrino and antineutrino running modes [8]. [The total signal statistics have been obtained by scaling the signal statistics reported in [8] by the ratio between 336 kt-MW-years (7 years) and 624 kt-MW-years (10 years) exposures.]) In these studies, we consider that there is no background contribution from wrong-sign or wrong-flavor neutrino candidates or neutral-current interactions.

Results—We first examine the effect of FSI modeling on reconstructed energy spectra relevant to $\bar{\nu}_\mu$ disappearance analyses, in both neutrino and antineutrino beam modes. Figure 2 shows the reconstructed oscillated spectra using different FSI models, overlaid with $\pm 0.4\%$ variations of Δm_{32}^2 . As indicated in the bottom panel in each subfigure, the shifts induced by FSI variations are comparable in size to the simulated variations of Δm_{32}^2 , and reproduce characteristic features of oscillation parameter variations near the first oscillation maximum corresponding to a shift in the energy spectrum. Additional figures comparing the FSI effects with corresponding variations in $\sin^2 \theta_{23}$ are provided in Supplemental Material [28].

A similar analysis is performed for the $\bar{\nu}_e$ appearance channel, which drives the sensitivity for identifying CP violation (CPV) and the precise measurement of the CP -violating phase δ_{CP} . Figure 3 shows the reconstructed ν_e and $\bar{\nu}_e$ spectra under the CP conservation ($\delta_{CP} = 0$) and maximal CPV ($|\delta_{CP}| = \pi/2$) hypotheses. When referring to maximal CPV across the study, we choose to only consider the case where δ_{CP} is $-\pi/2$, which is closest to the current knowledge [13]. Since sensitivity to measuring δ_{CP} depends on its value, this is shown alongside an error band of $\pm\pi/10$ or $\pm\pi/20$ for the CP -conserving and CP -violating cases, respectively, approximately corresponding to the projected precision reported in Refs. [3,8]. Across all four panels, the variations from FSI modeling are comparable to, or exceed, the size of spectral differences induced by varying δ_{CP} . However, as can also be seen by comparing the integrated event rate of CP -conserving case to the

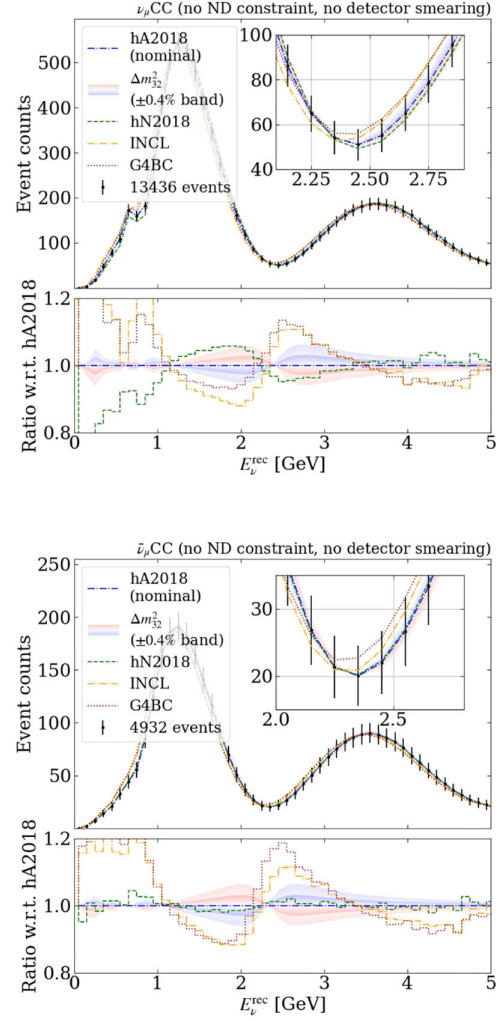


FIG. 2. Comparison of the simulated $\bar{\nu}_\mu$ reconstructed energy spectra and an oscillated DUNE experiment flux using different FSI models, to variations of Δm_{32}^2 . This is simulated for neutrino (top) and antineutrino (bottom) beam modes. In each subfigure, reconstructed energy spectra under different FSI models are shown as histograms and $\pm 0.4\%$ Δm_{32}^2 variations are shown with shaded red (+) and blue (−) bands centered on the hA2018 baseline. The error bars are broadly indicative of the DUNE experiment's statistical uncertainty with 10 years of operation. The inset provides an enlarged view of the first oscillation maximum. The lower panel displays ratios of FSI model and Δm_{32}^2 variations relative to the hA2018 baseline. In the lower panel, the bands show 1σ (inner) and 2σ (outer) variations to Δm_{32}^2 .

CP -violating case, the observation of CPV in the $\bar{\nu}_e$ appearance channel is clearly robust against considered FSI modeling variations if CPV is maximal. Whilst not shown here, we also studied the sensitivities to θ_{13} , the θ_{23} octant determination, and the neutrino mass ordering, concluding that the considered FSI modeling uncertainty has minimal impact on these measurements.

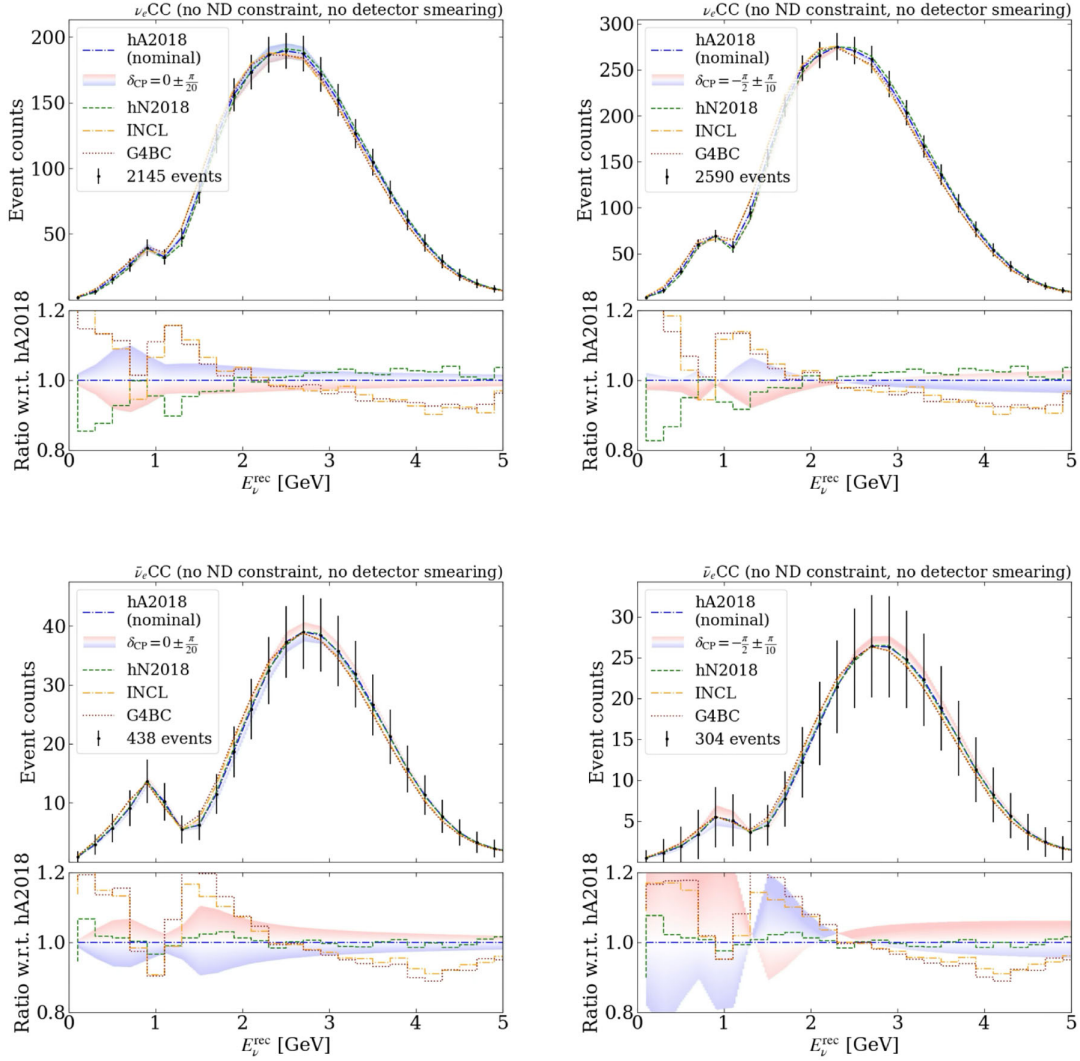


FIG. 3. Comparison of the simulated $\bar{\nu}_e^{(-)}$ reconstructed energy spectra and an oscillated DUNE experiment flux using different FSI models, to variations of δ_{CP} . This is simulated for neutrino (top) and antineutrino (bottom) beam modes. The left and right correspond to $\delta_{CP} = 0$ and $\delta_{CP} = -\pi/2$, respectively. Other figure elements follow the same conventions as described in Fig. 2, except that only the 1 σ uncertainty band is shown in the lower panels.

Discussion and outlook—Figure 1 shows that FSI changes the magnitude and shape of the bias in our proxy for the neutrino-energy reconstruction at DUNE. Changing the FSI model varies the number of (anti)neutrino events with more than 10% relative bias by about 30% (20%). Whilst not explicitly shown here, the evolution of the bias with neutrino energy is also changed (see Supplemental Material [28]). The FSI-induced modification in this bias manifests as spectral shifts and smearing in E_{ν}^{rec} . This affects the *measured* position of the first oscillation maximum, whose position as a function of *true* neutrino energy is determined primarily by the value of Δm_{32}^2 . This highlights a risk of degeneracy between FSI effects and Δm_{32}^2 variations. As shown in Fig. 2, the model spread from the baseline can exceed the spectral shifts induced by a 0.4% change in Δm_{32}^2 , particularly for the G4BC and INCL simulations.

In the case of true maximal *CPV*, our analysis indicates that the impact of FSI modeling is not likely to be decisive in the search for *CPV* since the majority of this sensitivity comes directly from the relative amount of observed electron neutrinos and antineutrinos rather than shape alterations in the reconstructed neutrino-energy spectra. However, the situation is different for precision measurements of δ_{CP} . In this case, the measurement can be influenced by effects that alter the shape of the reconstructed electron (anti)neutrino-energy spectrum, and the degree of sensitivity depends on the true value of δ_{CP} . As shown in Fig. 3, when $\delta_{CP} \sim -\pi/2$, variations in δ_{CP} primarily manifest as shape changes in the reconstructed energy spectra, whereas for $\delta_{CP} \sim 0$, they appear more as overall rate differences. Since the shape dependence resembles the effects introduced by variations in FSI modeling, we conclude that for precision δ_{CP}

measurements, FSI uncertainties may be significant if the true value of δ_{CP} corresponds to near-maximal CPV .

The results presented in this work offer a quantitative assessment of the impact of FSI modeling on E_ν^{rec} but are not representative of a systematic uncertainty for real oscillation analyses due to a number of limitations. First, we consider variations between FSI models as a proxy for their potential effect, neglecting the effect they will have on any constraint propagated from a near detector. In the case of DUNE, the near detector is clearly well equipped to constrain FSI modeling uncertainties [58], but doing so requires a currently unavailable comprehensive parameterisation of FSI to be fitted, alongside parameters describing other uncertainties, to the near detector data. The authors believe that the impact of this constraint cannot be meaningfully approximated with reasoning given in Supplemental Material [28]. Second, we only examine FSI variations on the size of the expected shape of the oscillated signal, neglecting its potential impact on backgrounds originating from sources such as wrong sign, wrong flavor, or neutral current interactions. Third, the effect of FSI variations on the reconstructed neutrino-energy spectrum is studied in isolation of other observables. It may be possible to choose an alternative set of far detector observables that could help disambiguate FSI effects from genuine neutrino oscillations (e.g., by using transverse or generalized kinematic imbalance variables [59–62]). (Regardless of the choice of observables, their relationship to the true neutrino energy remains a model-dependent mapping, which in turn must be accompanied by an appropriate uncertainty parameterization and therefore an improved understanding of FSI.) Fourth, we do not account for backgrounds to far detector event selections from neutral current interactions, neutrinos of the wrong flavor or sign, and the intrinsic electron neutrino contamination. Whilst these backgrounds are small for neutrino analyses ($\lesssim 20\%$ [8]) they can be large for antineutrino samples (up to $\sim 65\%$ [8]). The size and shape of the backgrounds will themselves also be impacted by FSI.

This work also does not consider potential variation of the reconstructed neutrino-energy spectra from sources of uncertainty beyond FSI. Modeling of other nuclear effects, particularly those that can significantly alter the hadronic system (e.g., hadronization), and detector response gives scope for significantly more variation. Although we consider only two sets of oscillation parameters, we expect that the qualitative conclusions of the study will not change for choices within the ranges allowed by experimental measurements [13].

Despite the above limitations, our analysis demonstrates the potential impact that varying FSI alone can have on reconstructed neutrino-energy spectra and compares it to oscillation parameter variations, showing scope for significant degeneracy between the two. Mitigating this will require future near detector systems to be able to precisely

characterize FSI. In particular, the more capable near detector [63] for DUNE Phase II will likely play a critical role in constraining interaction models through its enhanced ability to resolve final-state particles via low particle tracking thresholds. Moreover, the movable DUNE near detector system may be able to leverage the PRISM technique to remove oscillation measurement bias in FSI modeling in exchange for larger uncertainties [58].

Beyond near detector constraints, resolving FSI-driven degeneracies requires concerted theoretical guidance and dedicated experimental efforts. While hadron scattering on argon remains poorly constrained [6], modern LArTPC experiments including LArIAT [64] and ProtoDUNE [65,66] have begun using test beams to measure hadron-argon cross sections [67–70]. Although these measurements currently suffer from large uncertainties, future exclusive or differential analyses, potentially similar to carbon-target analyses from HADES [71,72], may offer significant discriminating power between different FSI models. These measurements should quantify the fraction of initial-state hadron energy visible in the final state, thereby constraining the shape of Fig. 1. Furthermore, FSI is being probed across various energies and channels by neutrino experiments including MicroBooNE [73], SBND [74], ICARUS [75], and the DUNE 2×2 prototype [76], complemented by precise electron-scattering data [77] and direct measurements on ejected neutrons [78–82]. Additionally, the proposed nuSCOPE experiment at CERN [83] offers event-by-event knowledge of *neutrino* energy and so would allow an almost direct measurement of the neutrino-energy bias shown in Fig. 1, covering the full range of energies of interest to DUNE.

Whilst the case study shown uses the DUNE flux and baseline, the qualitative conclusions are likely to be broadly applicable to any neutrino oscillation experiment relying on the calorimetric neutrino-energy reconstruction implied by Eq. (1). Conversely, the conclusions of this study cannot be directly translated to other methods of neutrino-energy reconstruction such as those used by HK, where FSI effects intervene primarily by altering sample composition via pion absorption [5].

Conclusions—In conclusion, this study quantitatively demonstrates that FSI modeling uncertainties have the potential to alter reconstructed neutrino-energy spectra in ways that are degenerate with variations of neutrino oscillation parameters. The variations in reconstructed energy spectra due to different FSI models are comparable to, or even exceed, the projected precision of next-generation experiments on Δm_{32}^2 and δ_{CP} . Whilst this is not directly illustrative of the size of FSI-related systematic uncertainties on oscillation measurements it highlights a critical need for improved FSI modeling, including a comprehensive uncertainty quantification to permit robust near detector constraints, supported by dedicated experimental measurements.

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Data availability—The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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